University of Southern Queensland
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Modelling of Electrokinetic Phenomena in Soils

By

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Abstract

The aim of this work was to develop theoretical methods for the prediction of remediation time and the electrical energy requirements for the remediation of soil contaminated with sodium chloride. Laboratory scale experiments were specially designed and performed on sand and clay samples at field capacity moisture content to identify the key features of electrokinetic processes in soil. The experiments confirmed the existence of a prominent ionic concentration or conductivity front travelling away from the cathode. The dissertation offers a novel theoretical explanation that links this front to the electronegative charge bound onto soil particles. A mathematical model of electromigration in soil is developed based on that theory. The model is essentially a set of partial differential equations (PDEs) with some coefficients behaving non-linearly. An algorithm for numerical solution of the PDEs is developed using a finite difference time domain approach. Reasonable agreement was found between laboratory test results and prediction of the corresponding numerical models. In addition, approximate analytical solutions to the PDEs allow remediation time and remediation energy requirements to be evaluated. The results of this work may be generalised to soils with ionic contamination other than sodium chloride.

Dedicated to
My very unique mother,
My dear father, and siblings,
My wife and children (Shaima, Sharafalden, Sufyan and Abdelmalek)

Certification of Dissertation

I certify that the ideas, experimental work, results, analysis, software and conclusion reported in this dissertation are entirely my own effort expect where otherwise acknowledged. I also certify that the work is original and has not been previously submitted for any other award, except where otherwise acknowledge.

Abdurrahman Feturi S. Huweg

Signature of Candidate Date

ENDORSEMENT

Dr. Tony Ahfock Date

Professor Steven Raine Date

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List of symbols and abbreviations

A Cross-sectional area of soil tube (m^2)

C Concentration of ions in (mol/l) or (C/m^3)

CEC Cation exchange capacity

C_i Concentration of species i ($moles/m^3$)

C_h Pre-treatment ionic concentration (C/m^3)

D Dielectric constant of the pore fluid (F/m)

D^* Diffusion coefficient (m^2 /s)

D_{eff} Effective diffusion coefficient in soil (m^2 /s)

dr Incremental distance normal to depletion surface (m)

dt Incremental time (s)

E Electric field gradient (V/m)

EC Electrical conductivity (S/m)

F Faraday constant (C/ mol)

GN_i Soil conductance due to negative ionic species (S)

GP_i Soil conductance due to positive ionic species (S)

H^+ Hydrogen ion

H Hydraulic head gradient

I Current through soil column (A)

I_{nd} Anionic current in the depletion region (A)

I_{nh} Anionic current in high conductivity region (A)

I_{pd} Cationic current in the depletion region (A)

I_{ph} Cationic current in the high conductivity region (A)

J Current density (A/m^2)

J_d Ion flux due to diffusion (mol /m^2. s)

J_i Total Flow rate of specific ion (mol /m^2.s)

J_m Migration flux of salt ions (mol /m^2.s)

J_n Anionic contribution to current density (A/m^2)

J_p Cationic contribution to current density (A/m^2)

I_s Electrode injected current (A)

K Anionic to cationic current ratio within the high conductivity region

K_e Coefficient of electroosmosis permeability (m^2/V.s)

K_h Hydraulic conductivity (m/s)

K_n Average anionic mobility (m^2 /V.s)

K_p Average cationic mobility (m^2 /V.s)

K_{pr} Pressure permeability coefficient (m^2/Pa.s)

L Length of soil tube (m)

L_{ac} Anode to cathode distance (m)

OH^- Hydroxyl ion

PDEs Partial differential equations

Q_w Electroosmosis flow rate (m^3/s)

R Universal gas constant (J /K mol)

RN_i Branch resistance representing electrical current carried by negative ions (Ω)

RP_i Branch resistance representing electrical current carried by positive ions (Ω)

r Radius of depletion surface (m)

R_{ac} Total anode to cathode resistance (Ohm)

S Speed of the depletion surface (m/s)

T Absolute temperature (K)

V Total applied voltage (V)

V_a Anode potential (V)

V_c Cathode potential (V)

W Remediation energy (Watt)

v_h Seepage velocity due to hydraulic gradient (m/s)

Z Charge number

Z_b Length of depleted region (m)

ε Soil electrical permittivity ($C^2/N.m^2$)

ζ Zeta potential (V)

η Viscosity of the pore fluid ($N.s/m^2$)

μ Mobility of ions in the electrolyte solution ($m^2/V.s$)

μ_{eff} Effective mobility of ion in soil (m^2 /V.s)

ρ Electrical resistivity (Ω m)

σ Soil electrical conductivity (S/m)

σ_d Soil conductivity in depletion region (S/m)

σ_h Per-treatment soil conductivity (S/m)

σ_{ni} Partial conductivity of soil at node i due to anion electromigration (S/m)

σ_{pi} Partial conductivity of soil at node i due to cation electromigration (S/m)

σ_m Minimum soil conductivity (S/m)

τ The soil tortuosity

φ Soil porosity

∇p Pressure gradient (Pa/m)

Δt Time interval (s)

ϕ Electrical potential (V)